GAS ACCRETION BY STAR CLUSTERS AND THE FORMATION OF ULTRALUMINOUS X-RAY SOURCES FROM CUSPS OF COMPACT REMNANTS

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ABSTRACT

Here we show that the overabundance of ultra-luminous, compact X-ray sources (ULXs) associated with moderately young clusters in interacting galaxies such as the Antennae and Cartwheel can be given an alternative explanation that does not involve the presence of intermediate mass black holes (IMBHs). We argue that gas density within these systems is enhanced by the collective potential of the cluster prior to being accreted onto the individual cluster members and, as a result, the aggregate X-ray luminosity arising from the neutron star cluster members can exceed $> 10^{39}$ ergs^{-1}. Various observational tests to distinguish between IMBHs and accreting neutron star cusps are discussed.

Subject headings: accretion;black hole physics; hydrodynamics; globular clusters: general

1. INTRODUCTION

Over the years, the existence of two distinct populations of black holes has been established beyond a reasonable doubt. Supermassive black holes, $M > 10^6 M_\odot$, are inferred in many galactic centers (Kormendy & Richstone 1995; Magorrian et al. 1998), while stellar mass black holes, $M \sim 1 - 10 M_\odot$, have been identified by their interaction with companion stars (McClintock & Remillard 2006). The situation at intermediate masses, $M \sim 10^2 - 10^5 M_\odot$, is still uncertain despite recent evidence for mass concentrations within the central regions of some globular clusters (Gebhardt et al. 2005; Ulvestad et al. 2007; Noyola et al. 2008). This evidence remains controversial, partly because the velocity dispersion profiles can be reproduced without invoking the presence of an intermediate mass black hole (IMBH) (Baumgardt et al. 2003,?; Anderson & van der Marel 2009).

Recently, some evidence has arisen for the presence of IMBHs in moderately young star clusters, where ultra-luminous, compact X-ray sources (ULXs) have been preferentially found to occur (Fabbiano et al. 2001; Trinchieri et al. 2008). Their high luminosities have been interpreted as imprints of IMBHs (Portegies Zwart et al. 2004), rather than binaries containing a normal stellar mass black hole (Zezas et al. 2006). In this *Letter*, we present an alternative explanation for the overabundance of ULXs associated with young clusters in galaxies such as the Antennae and Cartwheel. In this new paradigm, the accretion of gas by the collective star cluster potential moving through the merging medium is strongly enhanced relative to the individual rates and, as a result, the aggregate X-ray luminosity arising from the neutron star cluster members can exceed $> 10^{39}$ ergs^{-1}. Much of the effort herein will be dedicated to understanding the conditions by which the collective potential of a star cluster is able to accrete gas with highly enhanced rates and its effect on the integrated accretion luminosity of the neutron star cluster members. The conditions found in systems such as the Antennae galaxy, as we will argue, are favorable for this type of mechanism to operate effectively and produce an overabundance of ULXs.

2. ULX CUSPS FROM COMPACT STELLAR CLUSTER MEMBERS

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ULXs are seen in the star clusters of merging galaxies, such as the Antennae and the Cartwheel (Trinchieri et al. 2008; Zezas et al. 2006). These sources are compact in nature and in general associated with super star clusters (SSCs) - young, compact, massive clusters of stars (Zezas et al. 2002). Many of these sources have luminosities $\geq 10^{39}$ erg s^{-1}, which suggest that they could be IMBHs rather than binaries containing a normal stellar mass black hole.

A compact star of mass M_*, moving with relative velocity v through a gas of ambient density ρ and sound speed c_s, nominally accretes at the Bondi-Hoyle-Lyttleton rate: $\dot{M} \simeq 4\pi (GM_*)^2 \rho(v^2 + c_s^2)^{-3/2}$ (Edgar 2004). For a NS of mass $M_* = M_{\rm NS} = 1.4 M_\odot$ and radius $R_{\rm NS} = 10$ km, the corresponding X-ray luminosity is given by

$$L_X = \epsilon GM_{\rm NS} \dot{M} R_{\rm NS}^{-1} = 10^{32} n\epsilon \left(\frac{V}{10 \, \text{km/s}} \right)^{-3} \text{erg/s}, \quad (1)$$

where $\epsilon \leq 1$ is the efficiency for converting gravitational energy into X-ray radiation, $n = \rho/m_p$ is the hydrogen number density in units of cm^{-3} and $V = (v^2 + c_s^2)^{1/2}$. The integrated X-ray accretion luminosity of $N_{\rm NS}$ neutron star cluster members is then given by $L_X = 10^{36}(N_{\rm NS}/10^4) n\epsilon(V/10 \, \text{km/s})^{-3}$ erg/s.

In order for an aggregated accretion model to successfully describe ULXs, the predicted X-ray luminosity must naturally span the range of observed luminosities. This requires that the resulting speed V not be too large but more importantly that the external density be relatively high. Direct observational searches for cluster gas in the form of molecular, neutral, and ionized hydrogen have yielded non-detections, implying upper limits on the total gas content in the range of 0.1-10 $M_\odot$ (Smith et al. 1995). In a search for ionized gas Knapp et al. (1996) found upper limits of 0.1 $M_\odot$ within about one core radius for the clusters, implying $n_{\rm H+} \leq 50$ cm^{-3}.

A simple argument can be made to determine a lower limit to the density of the gas in the cores of globular clusters (GCs) in the absence of gas retention (Pfahl & Rappaport 2001). Suppose that the inner core of a GC contains $N_* = 10^2 N_{*,2}$ red giant stars, and so their mean separation is $r_\perp = 6.4 \times 10^{16} N_{*,2}^{-1/3} r_{\rm c,-1}$ cm, where $r_{\rm c} = 0.1 r_{\rm c,-1}$ pc. A lower limit on the wind density can be made by assuming that the wind of each of the stellar member extends only to its closest neighbors.

In this approximation, $n > n_w = 80 N_{*,2}^{2/3} r_{c,-1}^{-2} v_{w,1}^{-1} \dot{M}_{w,-7} \, \text{cm}^{-3}$, where $v_w = 10 v_{w,1} \, \text{km s}^{-1}$ and $\dot{M}_w = 10^{-7} \dot{M}_{w,-7} \, M_\odot \, \text{yr}^{-1}$ are the velocity and mass loss rate of the stellar core members. When the cluster gravity and the interaction between stellar winds is taken into account, we suspect that the gas density can be larger than this value.

For clusters that are moving through a relatively dense medium, as in Antennae galaxy for which CO measurements give $n \sim 10^3 \, \text{cm}^{-3}$ (Zhu et al. 2003), the collective external mass accretion is likely to shape the luminosity function for the accreting distribution of neutron stars. A density of 10^3 cm^{-3}, however, gives an aggregate neutron star luminosity of about $L_X = 10^{38} (N_{NS}/10^4) \, (\epsilon/0.1)(V/10 \, \text{km/s})^{-3}$ erg/s, which is not high enough to explain ULXs (Kalogera et al. 2004; Maccarone et al. 2007; Pfahl & Rappaport 2001). If, however, the collective potential of the cluster was able to significantly increase the surrounding gas density prior to being accreted onto the individual neutron star members, the aggregate X-ray luminosity could exceed 10^{39} erg/s. It is to this problem that we now turn our attention.

3. THE CLUSTER MODEL AND NUMERICAL METHOD

To test the gas density enhancement efficiency of a star cluster, we simulated a cluster potential moving through the merging galaxy medium at various typical velocities using FLASH, a parallel, adaptive mesh refinement hydrodynamics code. This scheme, and tests of the code are described in Fryxell et al. (2000). All star clusters are modeled here with a Plummer potential:

$$\Phi = \frac{GM_c}{(r^2 + r_c^2)^{1/2}} \tag{2}$$

Here, M_c is the total cluster mass, taken to be $3.5 \times 10^5 M_\odot$ (Zhang & Fall 1999; Gilbert & Graham 2007). We use several typical SSC cluster core radii, $r_c = 1, 2, 3$ pc (McCrady & Graham 2007). For comparison, Whitmore et al. (1999) estimates the typical half-light radius of the Antennae clusters to be (4 ± 1) pc. The core radius is expected to be significantly less than the half-light radius.

Our main goal is to examine the ability of a potential to accrete gas as a function of the relative speed of the potential through the gas, and the gas temperature. Our star cluster, here modeled as a Plummer potential, has been therefore set in motion through an initially uniform medium. The speed of sound far away from the cluster is taken to be $c_s \sim 10 \, \text{km s}^{-1}$, which is consistent with the inferred intracluster medium temperature $\sim 10^4 K$ in the Antennae galaxy (Gilbert & Graham 2007). Based on observations of several cluster knots in the Antennae galaxy, which indicate intracluster velocity dispersions of order $10 \, \text{km s}^{-1}$ (Whitmore et al. 2005), the initial Mach number of the cluster relative to the gas is varied between $\mu_\infty = v_\infty/c_s = 0.5$ to 4.0. Here, v_∞ and c_s are the velocity of the medium and the sound speed at infinity, respectively. The gas within the dense medium has a temperature selected to give the desired value of c_s and a density $\rho_\infty = 10^{-21} \, \text{g cm}^{-3}$, chosen to match the intracluster densities as derived from CO measurements (Zhu et al. 2003).

The effects of self gravity of the gas are ignored. This is adequate for most of our models, for which the accreted mass is less than the mass responsible for the potential. To improve the controlled nature of the models, we do not explicitly include radiative heating or cooling. The gas, instead, evolves adiabatically. The effects of radiative equilibrium are approximated by having the gas evolve with an adiabatic constant $\gamma = 1.01$, giving nearly isothermal behavior, which is consistent with the presence of a large quantity of dust near these clusters as inferred from infrared observations (Brandl et al. 2005). In cases where sufficient gas is accreted for it to become self-shielded, cooling could decrease the temperature of the gas significantly, potentially enhancing the accretion rate beyond the values computed here.

We use inflow boundaries on one side of our rectangular grid to simulate the cluster's motion through the ambient media. We run our simulations from initially uniform background density until a steady density enhancement forms in the cluster center, which usually takes a few 10-100 sound crossing times. Several models were run longer to test convergence and density enhancements were found to change only slightly with longer run times. We further tested convergence of our models for several resolutions and domain sizes. All tests produced similar density enhancements to those shown here. After hundreds of sound crossing times, the flow is relatively stable, and does not exhibit the "flip-flop" instability seen in two dimensional simulations (Blondin & Pope 2009).

4. RESULTING MASS DENSITY PROFILES AND ULX CUSPS

The accretion of ambient gas by moving bodies is a classical problem. Many studies have been focused on the flow around compact stars with a point mass potential. Although clusters have much larger masses than individual stars, their potential is relatively shallow and the classical treatment derived for a point-mass potential is only a fair approximation far from the cluster when $GM_c/r_c \gg c_s^2 + v^2$. When $GM_c/r_c \lesssim c_s^2 + v^2$, the collective potential alters the local gas properties before the gas is accreted onto the individual stars within the cluster.

Figure 1 shows the resulting density profiles for star clusters with $GM_c/r_c \sim c_s^2 + v^2$ for a variety of core radius and relative motions with respect to the external medium combinations. For small r_c, the potential starts to resemble that of a point mass and, as a result, the density enhancement in the central regions is very significant. A density enhancement is observed to persist as long as the sound speed or the relative velocity of the ambient medium is greater than the central velocity dispersion of the cluster. The enhanced density profiles within the cluster differ from the classical Bondi solution, and, for low Mach numbers, are better described by the cluster-Bondi analytic profiles derived by Lin & Murray (2007) as depicted in Figure 2. The profiles begin to deviate significantly from the cluster-Bondi solutions for high Mach numbers (inset in Figure 2).

The flow pattern around a star cluster at large relative velocities is multi-dimensional and complex (Figure 1). In the frame of the potential, the gas streamlines are bent towards the cluster center. Some shall intersect the center, while others converge along a line behind it. The convergence speed of the gas determines the reduction in its velocity relative to the potential due to shocks, and therefore whether or not the gas is accreted. In line with the conventional treatment, clusters moving with respect to the interstellar medium at increasing supersonic velocities will have density enhancements that are progressively lower and significantly more offset from the cluster's center. In these cases the aggregate mass accretion rate of the central neutron star is not significantly increased and stars accrete gas as though they move through the external medium independently. Because several gas knots in the

Antennae galaxy have velocities relative to the cluster of order the sound speed of the ambient medium, gas within these cluster cores would achieve high densities. Within this environment, accretion by the individual cluster members will be enhanced greatly relative to their rate of accretion directly from the ambient gas.

4.1. *X-ray Luminosities from Enhanced Accretion Rates*

Accretion and emission from the neutron star cluster strongly depends on the radial distribution of both compact remnants and gas. In this model, we calculate the expected X-ray emission from the neutron star members in the cluster using two extreme examples for the radial distribution of compact remnants. The first one is based on Fokker-Planck models of a core collapsed (centrally condensed) globular cluster (Dull et al. 1997), and the second simply assumes that the neutron stars, containing 1% of the total mass, follow the radial stellar mass distribution. The absorption corrected X-ray luminosities and characteristic emission frequencies of the neutron star cusps are calculated assuming a neutral absorbing medium with solar metallicity. Note that in this paper we consider neutron stars to be magnetic field free. If their fields are strong enough, the propeller effect may reduce the X-ray luminosity of neutron stars (Menou et al. 1999).

Figure 3 shows the aggregate X-ray luminosity of the accreting neutron star cluster as a function of the relative Mach number for both centrally condensed and non-condensed compact remnant distributions. The upper panel shows, for the centrally condensed case, how the absorption corrected X-ray luminosities vary with both photon energy and radial position within the cluster. As argued above, clusters moving with increasing supersonic velocities will have density enhancements that are progressively lower and significantly more offset from the cluster's center. As a result, the aggregate X-ray luminosity rapidly decreases with increasing Mach number (although less sharply for more extended clusters). While the density enhancement increases monotonically with decreasing relative velocity, so does the corresponding photoionization absorption. These two competing effects produce a maximum in the X-ray luminosity of the cluster at about $\mu_\infty = 2$. Most of the luminosity comes from 95% (60%) of all neutron stars in the condensed (non-condensed) distributions with X-ray luminosities ranging between 2×10^{34} (10^{33}) and 4×10^{34} (2×10^{34}) erg s^{-1}. In this regime, the results depend weakly on the assumed radiation spectra of the individual accreting members.

5. DISCUSSION

Many studies have been focused on the flow around compact stars with a point mass potential. Although clusters have much larger masses than individual stars, their potential is relatively shallow. In this paper we consider the efficiency of accretion in these cluster potentials, and show that when the sound speed or the relative velocity of the ambient medium is less than the central velocity dispersion of the cluster, the collective potential alters the local gas flow before the gas is accreted onto the individual stars within the cluster. Accretion onto these dense stellar cores at the inferred rate can lead to the onset of ULX sources.

While there are no stellar clusters observed in the Galactic disk which bear these anticipated properties (the relative velocity of the halo clusters to the interstellar medium is in the range of 100 km/s), observations of several cluster knots in the Antennae indicate intracluster relative velocities that comparable to the central velocity dispersions (Whitmore et al. 2005). Based on the results of the current work, we show that accretion by individual compact stars in the centers of such systems is enhanced greatly relative to their rate of accretion directly from the ambient gas, and conclude that this process may be relevant for explaining the origin of ULX sources in these extraordinary clusters. Illumination of nearby gas clouds by these sources may also lead to reprocessed infrared, optical and ultraviolet emission. Finally, the sources may leave trails of denser and likely hotter gas behind them as they plough through the gas.

A way to distinguish between an IMBH (Portegies Zwart et al. 2004) and an accreting neutron star cusp is via time-dependent observations. The emission from a relativistic region of a IMBH might vary on time-scales of seconds. The emission of a large number of statistically independent black holes and neutron stars should be considerably less variable: $\Delta t \leq r_{\rm c}/c_{\rm s} \sim 10^4$ yr. Observations find that a handful of the X-ray sources in the Antennae galaxy are indeed variable albeit on timescales that are larger than a few years (Zezas et al. 2006). Such variability might be explained if only a moderate fraction of the compact stars dominate the total luminosity. Such compact isolated accretors will probably have unusual time-variability properties as their discs may be much larger than the typical discs of X-ray binaries, and indeed they are missing the perturbing influence of the secondary. On the other hand, accretion disc feeding in these sources will be variable itself, leading to variability on variety of time-scales.

Although accretion disk spectra are notoriously difficult to calculate from first principles, an IMBH and a cluster core may also have observably different spectra. It has been suggested that a cool multicolor disk spectral component, might indicate the presence of an IMBH (Miller et al. 2003). This is understood as following. The larger mass of the BH accretor, the lower the temperature of the inner edge of the disk, which scales as $T_{\rm i} \propto (M_{\rm BH}\dot{M}/r_{\rm i})^{1/4} \propto \dot{M}^{1/4}M_{\rm BH}^{-1/2}$ for a simple thin-disk model. Since for our model, individual neutron star sources have $T_{\rm i} \sim 1$ keV (consistent with observations), then an IMBH might have $T_{\rm i} \sim 30$ eV. Thus, an association of the ULXs with an IMBH, as opposed to a accreting distribution of compact remnants, could be made on the basis of a very soft observed spectral component. We know of no reported observations of such components.
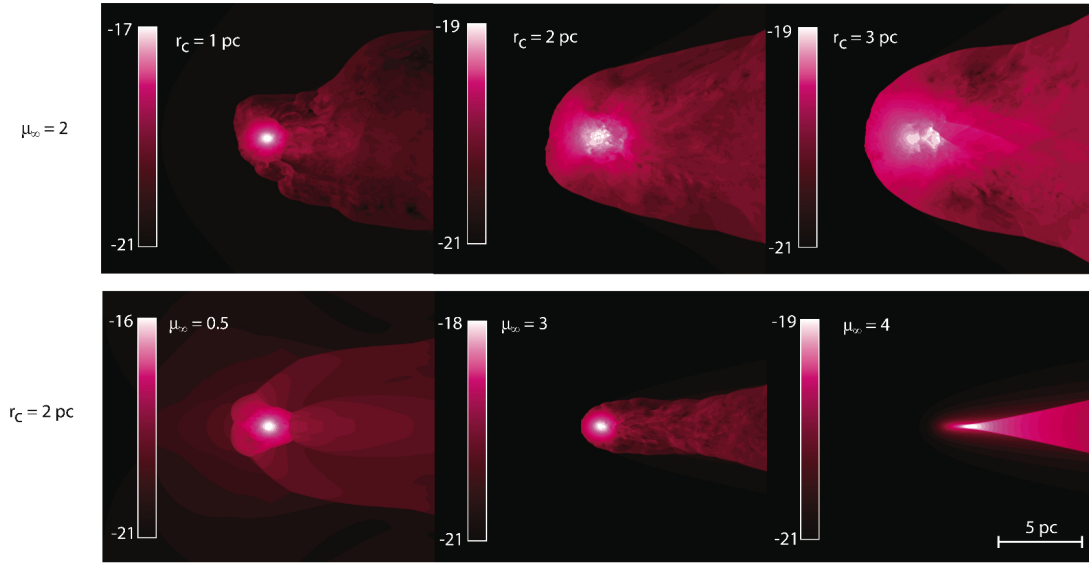
FIG. 1.— The flow pattern around a star cluster set in motion through an initially uniform medium with varying core dimensions (r_c) and relative speeds (μ_∞). Color bars show density cuts through the xy-plane in units of $\log(\text{g/cm}^3)$.
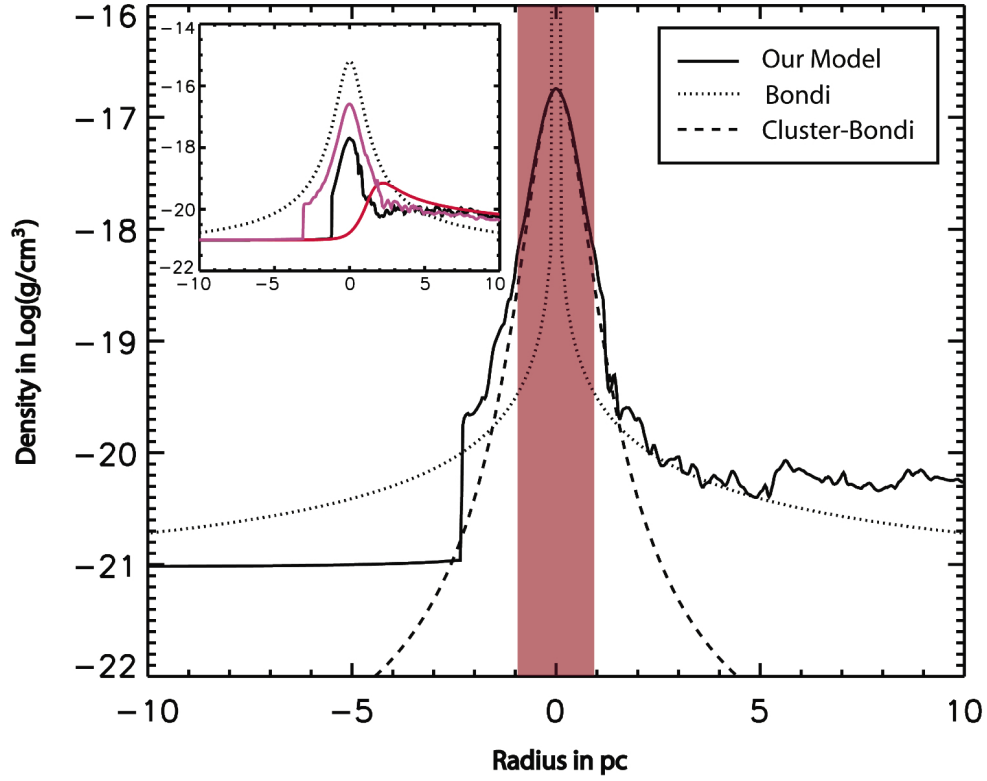
FIG. 2.— Density profile for a model with core radius $r_c = 1$ pc and $\mu_\infty = 2.0$. Solid black line shows a cut along the x-axis for the simulated cluster. The the dotted line is the Bondi solution for a stationary point mass, while the dashed line gives the renormalized Bondi-Hoyle-Lyttleton solution modified for a cluster potential as derived by Lin & Murray (2007). These modified solutions provide a good description of the density profile for $\mu_\infty \leq 1$ but not its normalization. As expected, these analytical solutions fail to reproduce the simulated flow for high Mach numbers as shown in the inset panel. *Inset:* The dotted line is the unnormalized cluster-Bondi solution while the light pink, black and red lines show the numerical profiles for $\mu_\infty = 2.0$, 3.0, and 4.0, respectively.
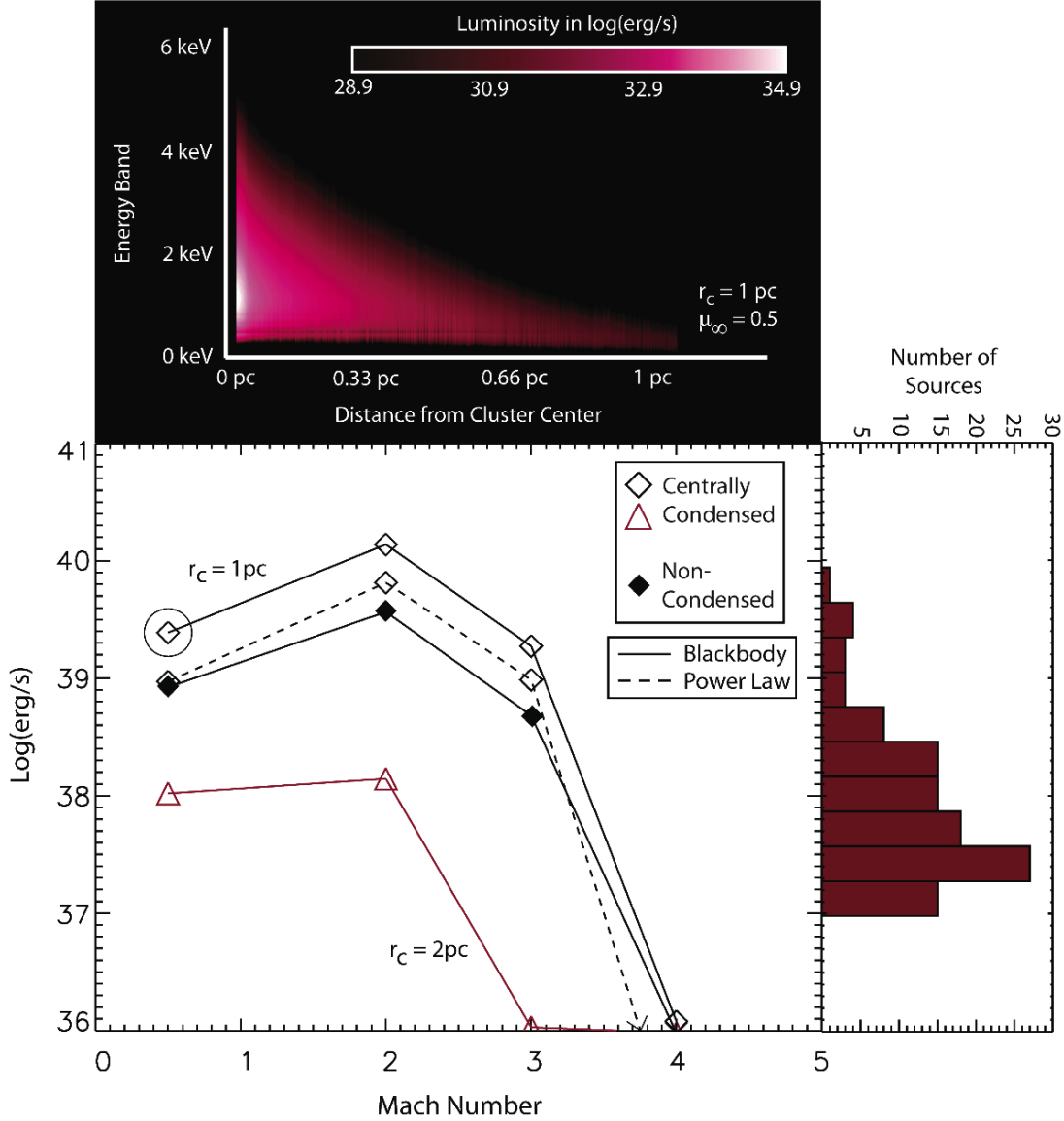
FIG. 3.— X-ray luminosities from enhanced accretion rates. *Center:* The absorption corrected X-ray luminosities from an accreting neutron star members in a star cluster as a function of μ_∞ calculated using two extreme examples for the radial distribution of compact remnants. Triangles are for $r_c = 2\,\mathrm{pc}$ while diamonds are for $r_c = 1\,\mathrm{pc}$. *Upper:* Spectral and luminosity decomposition as a function of distance from the cluster's center for a model with $\mu_\infty = 0.5$, $r_c = 1\,\mathrm{pc}$. *Right:* Luminosity distribution of the X-ray sources in the Antennae galaxy (Zezas et al. 2007).

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